

Proof of shock-excited H_2 in low-ionization structures of PNe

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Abstract. We report the detection of near-IR H_2 lines emission from low-ionization structures (LISs) in planetary nebulae. The deepest, high-angular resolution H_2 1-0 S(1) at $2.122 \mu\text{m}$, and H_2 2-1 S(1) at $2.248 \mu\text{m}$ images of K 4-47 and NGC 7662, obtained using NIRI@Gemini-North, are presented here. K 4-47 reveals a remarkable high-collimated bipolar structure. The H_2 emission emanates from the walls of the bipolar outflows and a pair of knots at the tips of these outflows. The H_2 1-0 S(1)/2-1 S(1) line ratio is ~ 7 -10 which indicates shock interaction due to both the lateral expansion of the gas in the outflows and the high-velocity knots. The strongest line, H_2 $v=1$ -0 S(1), is also detected in several LISs located at the periphery of the outer shell of the elliptical PN NGC 7662, whereas only four knots are detected in the H_2 $v=2$ -1 S(1) line. These knots have H_2 $v=1$ -0 S(1)/ $v=2$ -1 S(1) values between 2 and 3. These data confirm the presence of molecular gas in both highly (K 4-47) and slowly moving LISs (NGC 7662). The H_2 emission in K 4-47 is powered by shocks, whereas in NGC 7662 is due to photo-ionization by the central star. Moreover, a likely correlation is found between the H_2 $v=1$ -0 S(1)/ H_2 $v=2$ -1 S(1) and $[\text{N II}]/\text{H}\alpha$ line ratios.

1. Introduction

Optical imaging surveys of planetary nebulae (PNe) have revealed that a fraction of PNe possess, besides the large-scale structures such as rims, shells, haloes, some small-scale structures (e.g. [1], [2], [3]). These structures are prominent in the low-ionization emission lines such as $[\text{N II}]$, $[\text{S II}]$ and $[\text{O I}]$ (hereafter LISs). They exhibit a variety of morphologies like knots, jets, and filaments, ([3]), whereas they cover a wide range of expansion velocities from 30 km s^{-1} up to 350 km s^{-1} . Akras & Gonçalves ([4]), studying a sample of Galactic PNe with LISs, demonstrate that the excitation mechanism of these structures is a combination of UV-photons and shocks. The contribution of each mechanism depends on parameters like the distance of LISs to the central star, the stellar parameters (T_{eff} , L_{\odot}) and LIS's expansion velocity.

The physical properties like T_e , N_e and chemical abundances of LISs have been studied by different groups (e.g. [4], [5], [6]), and some of the most important conclusions are: i) there is no difference in T_e between the LISs and the nebular components, ii) LISs have systematically lower N_e compared to the surrounding medium (e.g. [4], [5]) and iii) there is no difference in chemical abundances that could provide an explanation for the enhancement of the low-ionization emission lines.

The formation models of LISs predict that they are denser structures than the surrounding ionized medium. This result is found to be inconsistent with the observations. A possible explanation for this discrepancy may be that the formation models refer to the total density of gas (dust, atomic and molecular) and not only to the N_e . Gonçalves et al. ([6]) have proposed that LISs may also be made of molecular gas. H_2 emission has been detected in the cometary knots in the Helix ([7], [8]) and knots/filaments in NGC 2346 ([9]).

Generally, H_2 emission has been detected in several PNe (e.g. [10]). A comparison of H_2 and optical line (e.g. [N II] and [O I]) images has revealed similar morphologies, suggesting that both emissions emanate from the same regions. A recent theoretical work by Aleman & Gruenwald ([11]) has shown that the peak intensities of the optical low-ionization and H_2 lines occur in a narrow transition zone between the ionized and neutral (photo-dissociation) regions. Moreover, an empirical relation between the fluxes of the [O I] $\lambda 6300$ and H_2 $v=1-0$ S(1) lines for Galactic PNe was reported by Reay et al. ([12]). Hence, the detection of strong low-ionization lines in LISs may also suggest the presence of H_2 gas.

2. Observations

The deepest, high-angular resolution H_2 $v=1-0$ S(1) at $2.122 \mu\text{m}$ and H_2 $v=2-1$ S(1) at $2.242 \mu\text{m}$ images were obtained for K 4-47 and NGC 7662 using the NIRI instrument on the Gemini-North 8 m telescope on Mauna Kea in Hawaii. For these observations, the f/6 configuration (pixel scale= 0.117 arcsec and field of view of 120 arcsec) was used. The exposure times were estimated using the empirical relation from Reay et al. ([12]). The final continuum-subtracted images are presented in Figures 1 and 2.

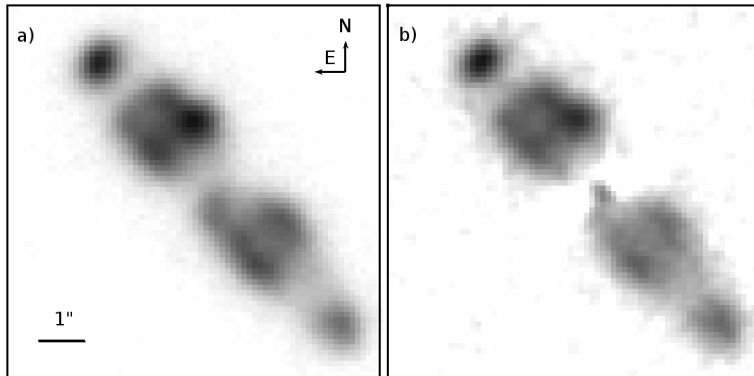


Figure 1. Line images of the bipolar planetary nebula K 4-47. (a) Continuum subtracted H_2 $v=1-0$ S(1), (b) H_2 $v=2-1$ S(1) emission lines.

3. Discussion

3.1. The highly collimated bipolar nebula K 4-47

The narrow-band near-IR H_2 images of K 4-47 (Fig. 1) reveal a remarkable high-collimated bipolar structure with the emission arising from the walls of the bipolar outflows. At the tips of these outflows lies a pair of fast-moving, low-ionization knots (100 km s^{-1} ; [13]).

These knots exhibit very strong [N I] $\lambda 5200$ and [O I] $\lambda 6300$ emission lines that are usually attributed to high-velocity shocks. Gonçalves et al. ([14]), running a number of shock models, came to the conclusion that the expansion velocity of these knots must be up to $250\text{--}300 \text{ km s}^{-1}$ in order to reproduce these lines. Despite their very high velocities, their H_2 $v=1-0$ S(1)/ H_2 $v=2-1$ S(1) line ratio is found to be ~ 7 , lower than the typical value of 10 for shock-excited regions ([15]).

Regarding the bipolar outflows, a comparison between our near-IR and optical images from [13] illustrates that the ionized gas (optical emission) is concentrated in a inner highly collimated structure, surrounded by the H_2 outflows. This structure of K 4-47 completely resembles that of

the M 2-9 and CRL 618 PNe indicating a possible connection among these objects. The large H_2 $v=1-0$ S(1)/ H_2 $v=2-1$ S(1) line ratio, estimated in the bipolar shell, was unexpected. Although, the recent hydrodynamic models by Balick B. and collaborators ([16]) can adequately explain our findings. The H_2 emission from the bipolar outflows can be explained as the result of the interactions between a jet or bullet with the AGB material. As the jet/bullet moves through the AGB material forms an conical structure that expands laterally outward with a velocity that increases with the distance from the central star. At the same time, the jet/bullet continues moving outwards, with a velocity proportional to the distance from the central star, dissociating the AGB H_2 gas, which later is being ionized by UV-photons (optical images). The surface brightnesses in the H_2 $v=1-0$ S(1) and H_2 $v=2-1$ S(1) emission lines are found to range from 0.2 to 1×10^{-15} erg cm $^{-1}$ s $^{-1}$ arc $^{-2}$ and from 0.2 to 1×10^{-16} erg cm $^{-1}$ s $^{-1}$ arc $^{-2}$, respectively.

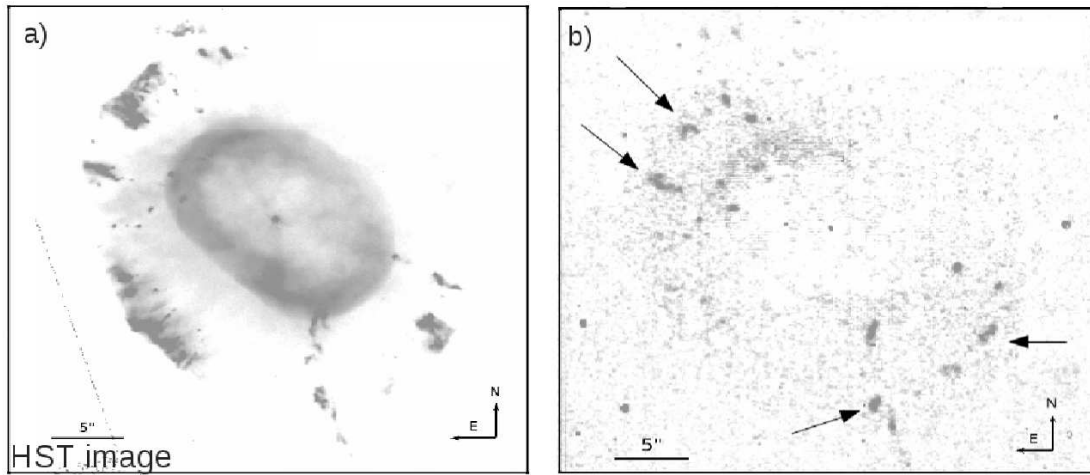


Figure 2. Continuum subtracted H_2 $v=1-0$ S(1) line image of the elliptical planetary nebula NGC 7662. The arrows indicate the four LISs in which the H_2 $v=2-1$ S(1) emission is detected.

3.2. The elliptical nebula NGC 7662

NGC 7662 is an elliptical PN that posses almost two dozens of LISs (knots and a jet-like structure) embedded in the outer shell with expansion velocities that vary from 30 to 70 km s $^{-1}$ (see [17]). All these structures are easily discerned in the [N II] line image ([18]), whereas spectroscopic data have revealed that they also exhibit a strong [O I] $\lambda 6300$ line ([17],[6]). Despite that the former line is a strong indicator of shock interactions, most of the LISs have low velocities except from the southern jet-like feature. (see [17]).

Here, we present the deepest near-IR images of this nebula. The H_2 $v=1-0$ S(1) emission line is detected in almost all optically identified LISs (Fig. 2, right panel.), whereas only four LISs are found to have H_2 $v=2-1$ S(1) emission. The former line is found to range from 1 to 4.8×10^{-16} erg cm $^{-1}$ s $^{-1}$ arc $^{-2}$, whereas the latter from 0.6 to 1×10^{-16} erg cm $^{-1}$ s $^{-1}$ arc $^{-2}$. No H_2 emission is found associated with the nebular shells. This confirms that LISs are likely molecular condensations embedded in a nebula. The value of H_2 $v=1-0$ S(1)/ H_2 $v=2-1$ S(1) line ratio is found to range between 3 and 5. These values imply that the LISs in this nebula are predominantly photo-ionized. Nevertheless, shocks cannot be discarded.

4. Conclusion

New, deep, high-angular resolution near-IR H_2 images confirmed the presence of molecular gas in fast- (K 4-47) and slow-moving LISs (NGC 7662). H_2 emission was also detected in the dense

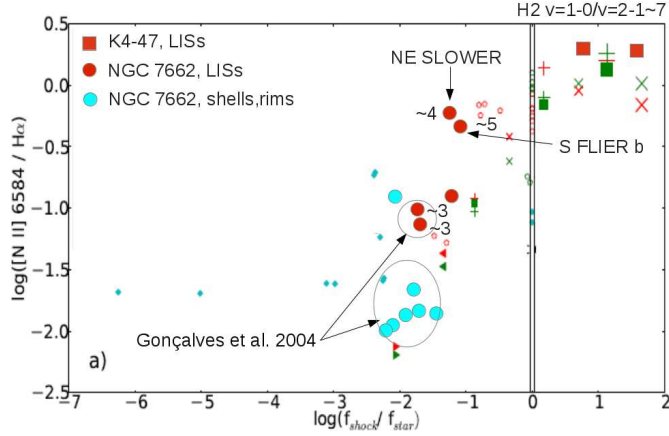


Figure 3. Plot of $[\text{N II}]/\text{H}\alpha$ vs. $\log(f_{\text{shocks}} / f_{\text{star}})$ for K 4-47 ([6]) and NGC 7662 ([17]) from the diagnostic diagram of Akas & Gonçalves ([4]) for photo-ionized and shock-excited regions. The numbers indicate the value of the H_2 $v=1-0$ $\text{S}(1)/\text{H}_2$ $v=2-1$ $\text{S}(1)$ line ratio from six LISs (the pair of knots in K 4-47 and the four knots in NGC 7662).

walls of the bipolar outflows of K 4-47 that implies a lateral expansion in agreement with the predictions from hydrodynamic models. Important morphological similarities among K 4-47, M 2-9 and CRL 618 have been found.

In the NGC 7662 nebula, H_2 emission was detected in several LISs, while it is totally absent in the nebular shells. Using the new diagnostic diagram from Akas & Gonçalves ([4]), and the spectroscopic data of the six LISs with measured H_2 $v=1-0$ $\text{S}(1)/\text{H}_2$ $v=2-1$ $\text{S}(1)$ line ratio, we found that the near-IR line ratio increases with the $[\text{N II}]/\text{H}\alpha$ optical line ratio (Fig. 3). This result may reflect a similar origin for the near-IR and optical line ratios. In conclusion, the H_2 emission in K 4-47 is powered by shocks, whereas in NGC 7662 is due to photo-ionization by the central star with a possible contribution of shocks.

Acknowledgments

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